TEMPORAL CHANGES IN SAGITTAL CURVATURE AND THE EMERGENCE OF LOAD PREDICTABILITY IN THE SHEEP RADIUS

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INTRODUCTION: An important aspect of achieving functional adaptation of a limb long bone is being able to control, and hence predict and respond to (e.g., by cortical thickness changes and osteonal remodeling), the spatial patterns of stresses that it experiences during normal use. In their landmark paper entitled "Bone Curvature: Sacrificing Strength for Load Predictability?" Bertram and Biewener (1988) [1] argue that this can be most efficiently and effectively achieved by controlling the direction of load-induced bending. This important goal of bone adaptation is called the achievement of "load predictability". Here we focus on quantifying ontogenetic variations that occur in whole-bone structure and cross-sectional geometry during growth of the sheep radius (with some curvature measurements also made on the ulna). Although the sheep radius has been extensively examined in studies of bone adaptation [2], little is known about how it morphologically changes during growth. It might be predicted that the diaphyses of neonatal sheep radii would lack sagittal curvature and that this curvature will emerge with maturation, because it ensures 'load predictability' that enhances the overall safety factor of the bone [1]. We hypothesized that during growth the diaphyseal curvature of the sheep radius changes in concert with additional biomechanically beneficial adjustments of the bone's structure/geometry: (1) cranial-caudal narrowing (and medial-lateral widening) of the cross-section, and (2) increased thickness of the relatively highly strained caudal "compression" cortex. The diaphyseal region of the sheep radius was examined because it is relatively simply loaded in cranial-caudal bending (net tension in cranial cortex and net compression in caudal cortex).

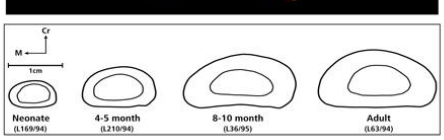
METHODS: Radii and ulnae from 10 newborn, seven 4-5 month old, seven 8-10 month old, and twelve 2-year-old sheep were used to measure longitudinal diaphyseal curvature ("bowing") along the cranial surface of the radius and the caudal surfaces of the radius and ulna. These measurements were made from the osteometric table to the bone surfaces at 20-80% of the bone length at 5% intervals. To account for differences in size of the bones between the four age groups, a cranial bow index (CrBi) was determined for the radius, and cranial and caudal bow indices (CrBi and CdBi) for the radius and ulna by dividing the maximum cranial or caudal bow height by the total length of the radius [3]. The radii were cut perpendicular to the length of the bone to make multiple segments at 40%, 50%, and 60%. Using the digital caliper, cortical thickness measurements were made directly from these sections at the cranial, caudal, medial, and lateral cortices, as well as the cranial-caudal and medial-lateral breadths. The 50% cross-sections were analyzed for Imax/Imin, cortical area, total area, medullary area, cortical robustness (cortical area/total area ratio (CA/TA expressed as a %)). One-way ANOVAs were used for statistical analysis, which was set at $p<0.05$.

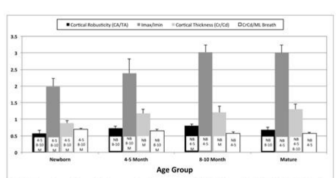
RESULTS (see Table and Figures): Longitudinal curvature of the sheep radius is minor in newborns and changes little from newborn to adult. By contrast, the ulna shows greater sagittal curvature in newborns and increases to a greater degree than the radius. CrBi of the radius is statistically different between the newborn and mature groups ($p=0.01$) where the mature radius is more significantly bowed (but the mean difference is very small). Statistically significant differences were found between all groups for the radius caudal bone index (CdBi), but these differences are also very small. By contrast, the CdBi of the ulna exhibits a: (1) 10% increase ($p=0.09$) from the newborn to the 4-5 month, (2) a 14% decrease from 4-5 month to 8-10 month, ($p=0.04$) and (3) little change from 8-10 month to adult. From newborn to 4-5 months the cross-sectional shape of the radius changes from quasi-annular to elliptical (relatively narrowed in cranial-caudal (Cr-Cd) direction). The Cd "compression" cortex is thicker in newborns but the Cr "tension" cortex becomes disproportionately thicker by 4-5 months and this persists in adults. The ratio of the overall cranial-caudal breadth of the bone (Cr-Cd breadth) vs. the medial-lateral breadth of the bone (M-L breadth) increases in the medial-lateral direction but not in the cranial-caudal direction which causes an apparent Cr-Cd narrowing ($p<0.001$ from 4-5 to mature). The Imax/Imin ratio of the radius also increased 54% from newborn to mature. But the increase was only 1.3% from 8-10 month to mature. The largest increase in the Imax/Imin ratio occurred between the newborn and 4-5 month group (by 20% ($p<0.0001$). All other between-group differences were significant ($p<0.0001$) except between the 8-10 month and mature ($p=0.6$) groups.

DISCUSSION: These results show that longitudinal curvature (which has the greatest influence on load predictability) of the radius diaphysis is relatively minor and is highly developmentally constrained, changing little from newborn to adult. By contrast, the ulna shows more curvature at birth, and its curvature increases at a relatively greater rate thereafter. Other morphological changes that also emerge appear to enhance Cr-Cd load predictability. Basic studies of how a bone's structure might emerge with respect to functional loading vs. genetic endowment includes that of Lanyon et al. (1980) [4]. They examined the morphology of the rat tibia after cutting the ipsilateral sciatic nerve in 4-week-old animals. The subsequent reduced motion resulted in a more rounded cross-sectional morphology of the ipsilateral tibia diaphysis when compared to the sharply angled (quasi triangular) tibia diaphysis of the control rats. The tibiae of neurectomized rats also failed to develop normal width, mass, and longitudinal curvature suggesting they are dependent on functional activity. Two hypotheses stem from their findings: (1) the "accommodation hypothesis", which suggests that bone form is developed to accommodate adjacent musculature, and (2) the "bone-strain hypothesis", which suggests that longitudinal curvature develops to optimize the level of functional strain in the bone tissue. The bone-strain hypothesis, which resembles some portions of the load predictability concept, argues that a functional strain level is maintained and that this exists within a range that provides a reasonable margin of safety between strains normally encountered and those that would cause excessive intracortical damage or frequent gross fracture. Maintaining a safety-factor relationship between customary strain and yield strain may be a principal modeling/remodeling goal of a limb bone. When a bone experiences strain levels below the tissue's physiologically optimum level and its external load orientations and magnitudes remain unchanged, it can establish higher strains by either of two methods: (1) establishing longitudinal curvature, and (2) reducing girth and cortical thickness, which works best if the bone is confined to longitudinal compression. Longitudinal diaphyseal curvature of the sheep radius could be caused by high strains but because the results of this study show that the curvature of the newborn radius is minor, and it is more likely that the radius and ulna sagittal curvatures function in concert to subsequently cause the higher strains as post-natal growth progresses. This is an important consideration when the sheep radius is used as a model for bone adaptation during growth and into the adult stage.

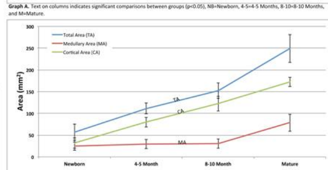
SIGNIFICANCE: These results help fill in a gap of knowledge regarding the growth of the sheep radius, which is an important model for studying cortical bone adaptation. The ulna likely plays an important role in ensuring load predictability because the curvature of the radius is relatively minor and changes little throughout ontogeny.

REFERENCES: [1] Biewener and Bertram 1988 J. Theoretical Biol; [2] Lanyon et al. 1979 J. Biomech.; [3] Kuo et al. 1998 J Biomed Mater Res, 40, 475-; [4] Lanyon et al. 1980 J Zool, London, 457-.





Graph A. Text on columns indicates significant comparisons between groups (p<0.05), NB=Newborn, 4-5=4-5 Months, 8-10=8-10 Months, and M=Mature.



Graph B.